Criteria for Selecting Object Coordinates at Probing by the Impulse UWB GPR with the "1Tx + 4Rx" Antenna System

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***Abstract*—An impulse UWB GPR antenna system consisting of one transmitter and four receivers has been designed for rapid detection of objects on, and under, the ground surface. The measured two-way times-of-flight for the reflected probing signals (from the radiator to the object and back to the four receivers) are used to calculate the (x, y, z) coordinates of the reflecting object. For cases where several reflected times-of-flight (due e.g. to reflections from the vehicle or other noise) are recorded, criteria enabling selection of unique coordinates that correspond to the true target have been determined and verified.**

Keywords—UWB radar, antenna system, detection of object, time-of-flight

I. INTRODUCTION

The UWB impulse ground penetrating radar (GPR) antenna system consisting of one radiator and four receivers arranged symmetrically in one plane has previously been proposed and described [1]. It was shown that this antenna system enables determination of all three coordinates (x, y, z) of a reflecting object and the velocity of the probing signal propagation based on measured times-of-flight (TOFs) of the probing signal from the radiator to the object and back to the receivers. Note that this does not require scanning or other movement of the antenna system. Target position can be calculated from reflected pulses recorded at the stationary array.

Due to energetic limitation the area that can be investigated by the real antenna system is limited. To extend this area it is proposed to move the antenna system over the area of interest using a robotic vehicle.

With a rapid pules repetition, targets can be quickly detected and positioned as the antenna system moves on a robotic vehicle. An obvious application for this system is landmine detection [2, 3].

During the latest experimental studies, it was observed that many reflections, and corresponding, TOFs, are detected in every receiver even when only one object is present. This is due to artifacts of the correlation algorithm for TOFs measurement, as well as variation of the UWB signal waveform based on the location and orientation of the object relative to the antenna system. In addition, there may be interference of signals, and system or ambient noise. The presence and/or combination of these multiple returns produces ambiguity in determining the unique presence and coordinates of actual objects. Criteria for identifying and discarding the "false" returns, and the resulting phantom coordinates of the object are proposed in this paper.

II. GEOMETRY OF THE PROBLEM

The antenna system consists of four receivers (Rx1, Rx2, Rx3, Rx4) and one central transmitter (Tx) symmetrically located in the horizontal plane, as shown in Fig. 1. The three dimensional (3-D) radius vector r of the object M defines the intersection of two planes, each of which passes through the corresponding pair of opposite receivers {Rx1 - Rx3} or {Rx2 - Rx4}, and terminates at the object itself.

Let us denote the TOFs of the probing pulse from the Tx to the object M, and then to each of the receiving elements Rx1, Rx2, Rx3, Rx4 as t_1, t_2, t_3, t_4, the in-plane distance

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from the origin of reference system to each of receivers as a, and the velocity of pulse propagation as v.

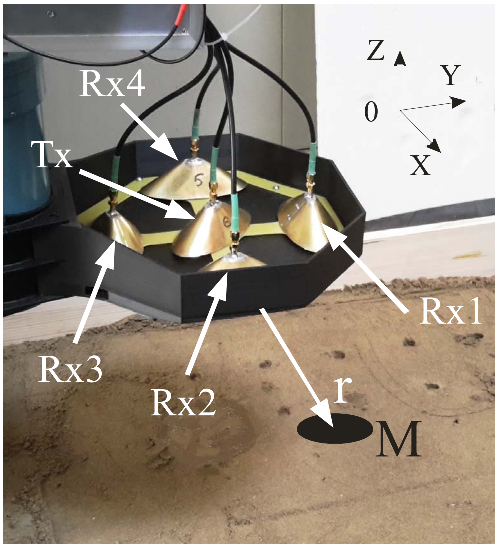

Fig. 1. Reference system, the "1Tx + 4Rx" antenna and object M. Center of the transmitter Tx coinsides with the origin of the coordinate system. The pairs of opposite receivers {Rx1 - Rx3} and {Rx2 - Rx4} are on the axises OY and OX correspondingly, symmetrically with respect to the origin.

For finding object coordinates in 3-D space, it is necessary to solve a pair of 2-D problems; one in each of the indicated (opposing receiver pair) planes. The geometry of the problem in the plane Rx4-M-Rx2 is shown in Fig. 2. Note that the axis OY* does not coincide with the axis OY of the original system; instead it is inclined from OY. The problem solution in each of the indicated planes gives the distance from the origin to the object and one coordinate of the object in the XOY plane. Using these data, we can find the coordinate of the object along the OZ axis.

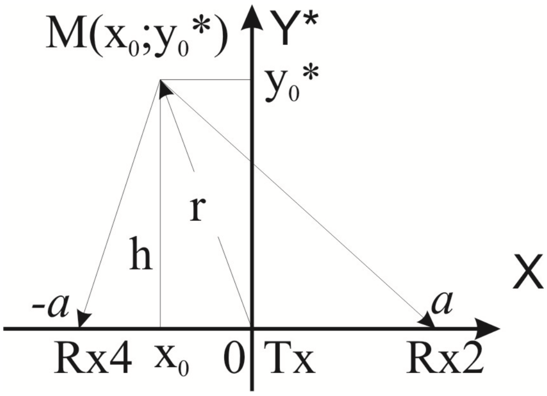

Fig. 2. The geometry of the problem in the plane Rx4-M-Rx2.

The algorithm for determining object coordinates is based on the equality of the areas of the triangles, in each opposing receiver pair plane, whose sides are the flight trajectories of 1) the probing pulse from the radiator to the object, 2) from the object to the receiver, and 3) from the origin to the receiver.

III. Problem of Unique Determination of TOFs

For these experiments, a simulant of the PMN-4 plastic-cased mine was buried in a sand test bed at natural moisture content. The antenna system was mounted on a robotic platform that moved continuously along the OY axis, performing measurement cycles in search of the object. Each measurement cycle or step consisted of radiation of the probing impulse UWB signal, and recording of reflections received by all four receiving antennas one-by-one. Each step required approximately 40 ms.

The initial data for positioning of the object are the recorded TOFs as determined by an algorithm based on the Pearson correlation [4] between the radiated signal and the waveform of the reflections at the receivers. In practice, it is observed that this algorithm identifies several TOFs, even if there is only one object along the scanning path. This is due to the reflected UWB signal pulses having different shapes due to the scattering at different angles of short electromagnetic impulses when reflected by a large non-planar object with variously-oriented surfaces in 3-D. A-priori, we do not know which of the combinations of TOFs relate to the real object, and which ones correspond to the "phantoms" from interference, unwanted vehicle reflections, system noise, etc. Therefore, it is a necessary first step to compute all possible coordinates of suspected objects using all possible combinations of 4 TOFs. Then, the problem becomes how to objectively choose those which could realistically correspond to the real object.

To better illustrate the problem, consider first a typical radar signals such as that shown in Fig. 3. This probing signal was obtained by total reflection of the radiated pulse by a metal sheet located on the floor.

Now, let the reflecting object (a simulant PMN-4 landmine) be located on the laboratory floor under the receiving antenna Rx1. In this case, the signals received by all four receiving antennas Rx1 through Rx4 have the shapes, as shown in Fig. 4 and 5.

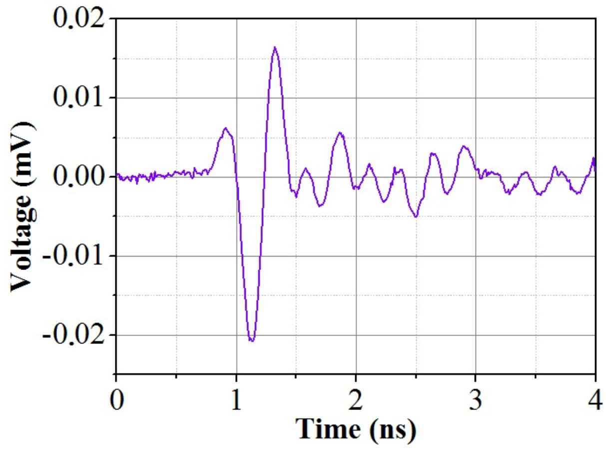

Fig. 3. A typical probing signal.

As expected, the strongest signal is received by the antenna Rx1. This is because this antenna is located directly above the object and at the shortest distance. The weakest signal is received by the most distant antenna Rx3.

Observing the reflected waveforms in Figs. 4 and 5, one can identify several sections of each with shape close to that of the perfectly-reflected probing signal (Fig. 3).

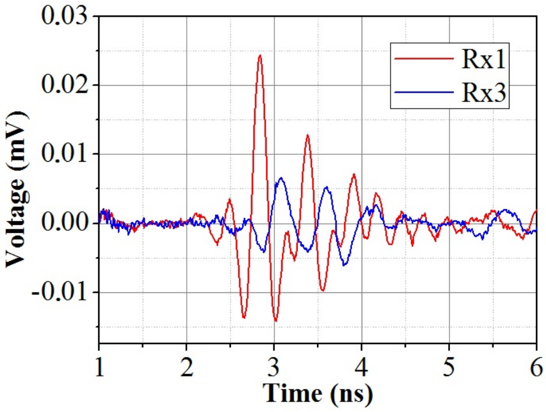

Fig. 4. The signals received by antennas Rx1 and Rx3 from a PMN-4 simulant on the floor beneath Rx1.

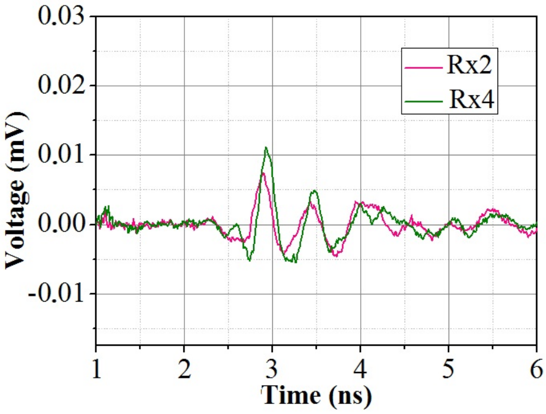

Fig. 5. The signals received by antennas Rx2 and Rx4 from a PMN-4 simulant on the floor beneath Rx1.

The Pearson correlation algorithm compares the received signal waveforms from the PMN-4 simulant (Figs. 4 and 5) with the perfect reflection (Fig. 3), and produces several peak values at different time shifts. These represent possible TOFs for each receiver Rx1 through Rx4 as listed in Table I.

TABLE I.

Receivers	TOFs (ns)			
Rx1	2.103	2.493	3.033	3.233
Rx2	2.123	2.613	3.253	
Rx3	2.303	2.813	3.323	
Rx4	2.183	2.673	3.153	3.303

Thus, in this experiment, we obtain 12 possible positions of the target for calculations in the Rx1-M-Rx3 plane and 12 possible positions for calculations in the Rx2-M-Rx4 plane. The resulting total number of possible combinations is 144, but only one combination of TOFs gives the true coordinates of the target. This motivates the need for objective criteria for selecting the true object position.

IV. Criteria for Selection

The process for discriminating the TOF combination corresponding to the real object involves 5 steps.

1) We analyze all possible combinations of TOFs t_1t_3 and t_2t_4 at each step. We leave only those combinations, which satisfy conditions for the existence of the triangles Tx-M-Rx1, Tx-M-Rx3, Tx-M-Rx2, Tx-M-Rx4, Rx1-M-Rx3, and Rx2-M-Rx4. Namely, they are

$$t_1 \geq \frac{a}{v}, t_2 \geq \frac{a}{v}, t_3 \geq \frac{a}{v}, t_4 \geq \frac{a}{v}, \frac{2a}{v} \geq |t_1 - t_3|, \frac{2a}{v} \geq |t_2 - t_4|$$

From the remaining combinations, we create the following ones t_1t_3 and t_2t_4. If the number of combinations t_1t_3 is equal to n, and the number of combinations t_2t_4 is equal to m then the number of all combinations t_1t_3 and t_2t_4 is equal to $n \times m$ at each step.

2) For each pair t_1t_3 and t_2t_4 we calculate the distances r_1 and r_2 to the object in both planes. We choose only those combinations of pairs t_1t_3 and t_2t_4, for which Δr is sufficiently small. The distance $r = (r_1 + r_2)/2$ is assumed to be distance to the object.

3) For these combinations, using the algorithm for determining object coordinates, we calculate the coordinates x_0, y_0 of possible objects; and among them we choose those corresponding to $x_0^2 + y_0^2 < r^2$, and these allow calculation of the coordinate z_0.

4) Among the multiple coordinates x_0, y_0, z_0, we choose the physically reasonable ones. For example, an object cannot float above the surface of the earth, and this imposes a condition on the value z_0.

5) Then we compare the results of the coordinate calculations step-by-step for the moving the antenna system. After trying several steps among all possible combinations of coordinates, we choose those for which the coordinate y_0 will progressively decrease (as the antenna system approaches the object) while coordinates x_0 and z_0 remain nearly constant. The change in coordinates with each step must be consistent with the known movement of the antenna system. That is, the distance to the object r must decrease smoothly (as the antenna system approaches the object) or increase smoothly (as the system moves away from the object).

If the above conditions are satisfied after several steps, the motion of the antenna system can be stopped, and the coordinates of the object will correspond to the last calculated combination that satisfies all of the above-listed conditions.

V. Results of Selection

In the experiment to test this procedure, we collected reflected signals during movement of the antenna system over a stationary object, and post-processed them. The projections onto the XOY plane of all points whose coordinates satisfy the criteria 1 through 4 are shown in Fig. 6. Results of selection after adding criterion 5 are shown in Fig. 7.

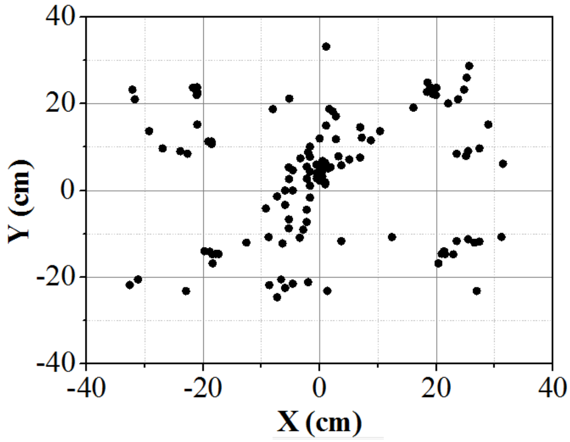

Fig. 6. Projection onto the antenna system plane of all points whose coordinates satisfy the criteria 1 through 4.

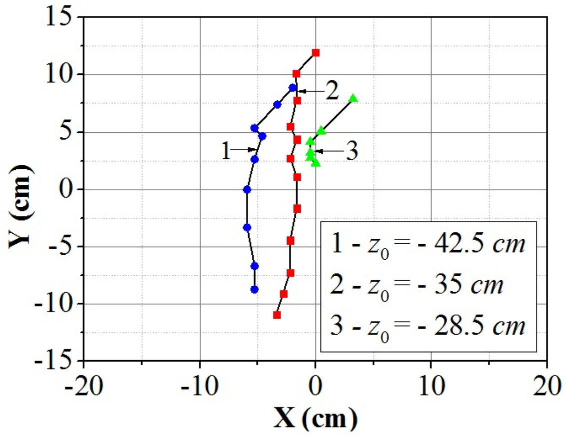

Fig. 7. Results of target coordinate selection after application of all 5 criteria.

Three groups of coordinates are identified, which correspond to 3 possible objects located at a distance $|z_0|$ of 28.5 cm, 35 cm and 42.5 cm down from the coordinate origin at the Tx antenna. The objects become apparent when the distance from the object to the projection onto the XOY plane of the origin does not exceed 12.5 cm. Although path 3 has variation of y_0 with stable x_0 and z_0 it cannot represent the true object because it does not completely satisfy criterion 5, with incremental steps in y_0 that are not close to equal.

When analyzing the graphs in Fig. 7, we can infer that paths 1 and 2 correspond to the same object, but the reflections come from different surfaces. Maximal difference between X coordinates of the object along path 1 and 2 is less than 5 cm - which is only a half of the object diameter.

Fig. 8 presents graphs of dependence of the distance r from the origin of coordinates to the object, represented step-by-step for these three possible objects.

Analyzing Fig. 7 and Fig. 8, we can see that the object is firstly in front of the antenna system, and the distance r from the origin to the object is the largest. For the top two graphs, as the system approaches the object, the distance r decreases, producing the smallest value when the system is directly above the object. As the antenna system goes further away from the object the distance r increases.

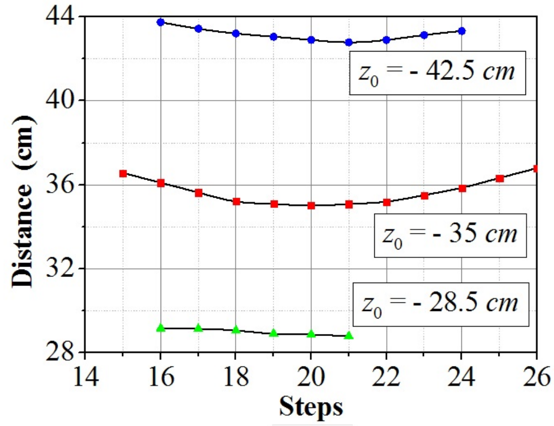

Fig. 8. Variation distance r to the object at movement of the antenna system.

VI. Conclusion

The impulse UWB antenna system consisting of one radiating and four receiving elements was used to determine the coordinates of the object. The algorithm in which the initial data for the positioning of the object are the measured TOFs of the probing signals from the radiator to the object and back to the receivers was proposed. The algorithm for determining object coordinates has been supplemented by formal criteria enabling discrimination of coordinates that correspond to the real object from artifacts or phantoms. In order to discriminate the real object, we additionally used a sort of digital spatial filter which uses information on the trajectory of movement of the antenna system. Experimental testing has shown that selection using the full set of criteria allows detection of the simulant PMN-4 landmine in the sand test bed, and calculation of its true coordinates with precision better than the target diameter.

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